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Cloud-Scale Numerical Modeling of the Arctic Boundary Layer

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Summary of Research

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Table of Contents

1	Summary of Research	1
1.1	Arctic Stratus Clouds	1
1.1.1	Smoke Cloud Intercomparison	1
1.1.2	Turbulence Closure Model Simulations of Arctic Stratus Clouds	1
1.1.3	Large-Eddy Simulations of an Arctic Stable Cloudy Boundary Layer	2
1.2	Modeling the Effects of Leads Upon the Atmosphere and the Surface Heat Budget of the Arctic Ocean	3
1.2.1	Activities	4
1.2.2	Findings	6
1.3	Figures	13
2	Students and Postdocs Supported	18
3	Bibliography	18
	Appendix: Selected Reprints, Preprints, and Reports	20

1 Summary of Research

The research objectives of this project were:

- To determine in detail how large-scale processes, in combination with cloud-scale radiative, microphysical, and dynamical processes, govern the formation and multi-layered structure of *Arctic stratus clouds*. This information will be useful for developing and improving 1D boundary layer models for the Arctic.
- To quantitatively determine the *effects of leads on the large-scale budgets* of sensible heat, water vapor, and condensate in a variety of Arctic winter conditions. This information will be used to identify the most important lead-flux processes that require parameterization in climate models.

Our approach was to use a high-resolution numerical model, the 2D University of Utah Cloud Resolving Model (UU CRM), and its 1D version, the University of Utah Turbulence Closure Model (UU TCM), a boundary layer model based on third-moment turbulence closure, as well as a large-eddy simulation (LES) model originally developed by C.-H. Moeng.

1.1 Arctic Stratus Clouds

1.1.1 Smoke Cloud Intercomparison

An intercomparison of radiatively driven entrainment and turbulence in a smoke cloud (Bretherton et al. 1997) investigated an idealized case in which a convective boundary layer filled with radiatively active "smoke" is simulated by several 1D, 2D, and 3D models. We used this case to test the UU TCM. The results using the UU TCM agree well with the 3D large-eddy simulations involved in the intercomparison (Krueger et al. 1999a).

1.1.2 Turbulence Closure Model Simulations of Arctic Stratus Clouds

We investigated the sensitivity of the formation and structure of simulated Arctic summertime boundary-layer clouds to large-scale vertical velocity and drizzle using the UU TCM (Krueger et al. 1999b). The baseline case, under conditions of no large-scale vertical motion, contains two layers of clouds: a

stable fog layer near the surface and a stratus cloud in an elevated mixed layer. We found that large-scale subsidence delays the formation of the upper cloud layer, and increases the liquid water content of the fog layer. Neglecting drizzle has little impact on the cloud water mixing ratios in the upper cloud layer, but significantly increases them in the fog layer.

1.1.3 Large-Eddy Simulations of an Arctic Stable Cloudy Boundary Layer

The purpose of this study was to assemble the FIRE ACE/SHEBA observations for LES research and to evaluate the performance of an LES model in simulating a stable cloudy boundary layer (Zhang et al. 2000; Zhang and Krueger 2000). A stable Arctic cloudy boundary layer was observed by aircraft flights on 23 July 1998 during the FIRE ACE (First ISCCP [International Satellite Cloud Climatology Project] Regional Experiment Arctic Clouds Experiment). The boundary layer was characterized by strong wind shear and a pronounced temperature inversion. In the boundary layer, there was a surface fog with its top at about 210 m. There were other two cloud layers above this layer: one consisting of altocumulus and one of cirrus.

We analyzed this case and assembled a data set for initializing, forcing and evaluating LES. Our research was focused on the stable boundary layer below 500 m where the surface fog was located. Our LES experiments focused on the stable boundary layer (below 500 m) where we make comparison with observations. Our simulations indicate that the LES model is able to provide reasonable mean profiles of the horizontal wind, temperature, humidity and cloud liquid water. The model's ability to replicate the observed turbulent structure was investigated. However, this was difficult due to substantial differences between the two available analyses of the turbulence measurements.

We found that the turbulence of this boundary layer is driven primarily by wind shear. We also found that in simulations that included an upper cloud layer, the upper cloud layer had an influence on the evolution of the lower cloud layer.

Sensitivity experiments were made to study the physical processes occurring in the boundary layer. In order to investigate the role of radiative cooling as well as wind shear in maintaining turbulence of the boundary layer, we made two additional sensitivity simulations (without wind shear and without radiation, respectively). In the simulation without wind shear, the turbulence was very weak. It demonstrates the importance of the wind

shear in maintaining the turbulence of the boundary layer. In the simulation without radiation, the turbulence was comparable with that in the base simulation, in which both the effect of wind shear and the radiative effect were considered. Therefore, we concluded that the turbulence of the boundary layer was driven primarily by wind shear.

Multiple cloud layers were observed in this case. We investigated the effect of the upper level cloud layer on the evolution of the surface cloud layer. In the simulation which did not include upper level clouds, radiative cooling was large and more cloud water was simulated compared with those in the simulation with the upper cloud layers. It shows that the existence of the upper cloud, which emitted radiation down and reduced the cooling in the lower cloud layer, prevented the lower cloud layer from further development.

1.2 Modeling the Effects of Leads Upon the Atmosphere and the Surface Heat Budget of the Arctic Ocean

This project extended previous lead-resolving modeling by including all of the important small-scale processes. Previous modeling studies had either neglected or crudely treated one or more of the following processes: finite width of lead, turbulence, cloud formation, radiative transfer, and/or conductive heat flux through the ice and snow. This project is also the first to use observed mid-winter SHEBA observations as the basis for the simulations, and the first to simulate an elevated, lead-generated ice cloud similar to the one observed at SHEBA when the ice camp was located downwind of a large lead. And this project is the first to use a lead-resolving simulation to evaluate the mosaic method of parameterizing the effects of leads, which is commonly used in global climate models. We concluded that the mosaic method is inadequate to represent the atmospheric effects of leads.

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This research is described in more detail in Zulauf's dissertation (Zulauf 2001), in two papers based on Zulauf's dissertation (Zulauf and Krueger, 2002a,b), and in three conference preprints (Zulauf and Krueger 1999, 2000,

2001).

The following summary is based on the Final Report submitted for NSF Grant OPP-9702583 entitled "Modeling the Effects of Leads Upon the Atmosphere and the Surface Heat Budget of the Arctic Ocean."

1.2.1 Activities

The interactions between sea ice, open ocean, atmospheric radiation, and clouds over the Arctic Ocean exert a strong influence on global climate. Uncertainties in the formulation of interactive air-sea-ice processes in global climate models (GCMs) result in large differences between the Arctic, and global, climates simulated by different models. Open and recently frozen leads (channels of open water in sea ice) have significant impacts on the large-scale budgets during the Arctic winter, when they contribute about 50 percent of the surface fluxes over the Arctic Ocean, but cover only 1 to 2 percent of its area. Convective plumes generated by wide leads have been observed to penetrate the surface inversion and produce condensate that spreads up to 250 km downwind of the lead. Lead-generated convective plumes may significantly affect the longwave radiative fluxes at the surface and thereby the sea ice thickness. The effects of leads and boundary layer clouds must be accurately represented in climate models to allow possible feedbacks between them and the sea ice thickness.

The SHEBA (Surface HEat Budget of the Arctic) field experiment documented a complete annual cycle of a drifting floe of Arctic sea ice, the ocean below it, and the atmospheric column above it. The evolution of the properties of the sea ice and the surface heat budget components were obtained from a variety of instruments. Atmospheric measurements included profiles of temperature, humidity, and wind obtained from twice-daily radiosonde launches, and continuous lidar and radar observations of clouds. Satellite measurements revealed the distribution of leads and thin ice in the vicinity of the SHEBA ice camp. Although no aircraft measurements were made over leads during mid-winter, the SHEBA dataset is still the most comprehensive yet obtained of Arctic mid-winter conditions, and nevertheless offers an opportunity to significantly improve our ability to represent the important effects of leads upon the atmosphere and the surface heat budget of the Arctic Ocean in GCMs.

We used two high-resolution numerical models, the 2D University of Utah (UU) Cloud Resolving Model (CRM) and the 3D UU Large Eddy Simulation

(LES) model, to increase our understanding of (1) how atmospheric convective plumes emanating from leads affect the large-scale atmospheric budgets of sensible heat, water vapor, and condensate, and (2) how the contribution by such plumes to Arctic cloud cover, directly through the production of clouds and indirectly by increasing boundary layer moisture, affects the surface heat budget of the Arctic Ocean.

We began with idealized simulations to better understand the dependence of lead-generated convective plumes on various factors. We used the 2D CRM to simulate the circulation, condensate plume, and other local effects produced by an individual lead for various lead widths (from 200 m to 10,000 m), lead orientations (relative to the wind direction), atmospheric conditions, and model physics. We used the 3D LES primarily to evaluate the 2D CRM results.

The simulations described above did not include microphysical or radiative transfer processes, nor was the surface temperature of the snow or ice allowed to respond to changes in the net surface heat flux. We used 2D CRM simulations with different levels of physics to gauge the impacts of including these physical processes. We looked at results from four configurations. The first is with no additional physics; the second is with the addition of microphysical processes; the third is with the addition of microphysical and radiative transfer processes, and the fourth includes heat transfer through the snow and ice to allow the surface temperature to evolve.

To allow heat transfer through the snow and ice, we modified the CRM so that the temperature profile in the snow/ice layer is integrated forward in time by the one-dimensional heat conduction equation. The snow and ice thicknesses are now prescribed (using typical values observed at SHEBA), and the temperature at the snow surface is determined so that the net IR, sensible, and latent heat fluxes are balanced by the conductive heat flux through the snow/ice layer.

Because the large-scale effects of lead-generated plumes depend strongly upon ambient conditions, we decided it was necessary to progress to simulations based upon the actual conditions at the SHEBA ice camp. For this purpose, we used the soundings for 18 Jan 1998 (which appeared to be typical of the clear sky conditions), as the basis for a set of simplified atmospheric profiles of temperature, relative humidity, and wind velocity to use in our simulations. We then quantified the large-scale effects of lead-generated plumes based on "full physics" CRM simulations (which include microphysical and radiative processes, and interactive snow surface temperatures) run

for typical mid-winter SHEBA conditions.

We used the SHEBA mid-winter measurements as the basis of a series of CRM simulations designed to increase our understanding of (1) how atmospheric convective plumes emanating from leads affect the large-scale atmospheric budgets of sensible heat, water vapor, and condensate, and (2) how the contribution by such plumes to Arctic cloud cover affects the surface heat budget of the Arctic Ocean. Figure 4.3 (see section 1.3) shows the observed atmospheric soundings from SHEBA rawinsondes for January 18, 1998, 23:16 UTC and the simplified profiles used in initializing the CRM.

The effects of changing the lead width were also examined. To examine the effects of lead refreezing, a simulation was run in which the lead was covered with a 2.5 cm thick layer of ice. In another simulation, the ambient relative humidity was decreased with respect to the basic simulation.

We also examined the commonly used "mosaic" method for parameterizing the effects of leads on surface turbulent fluxes in large-scale models. A one-dimensional version of the CRM was used in which the surface fluxes are a weighted average of fluxes calculated over water and snow/ice. The resulting simulation evolve in time, and includes cloud, radiative, and turbulence feedbacks.

The research activities described above relied on the UU CRM. In addition, M. Zulauf developed the UU LES, a 3D nonhydrostatic model based on the quasi-compressible outflow model (QCOM) described in Droegemeier and Williamson (1987). It includes a prognostic equation for the sub-grid scale turbulent kinetic energy, and a stability-dependent surface flux parameterization. At this time it is well suited for modeling small-scale three-dimensional atmospheric flows, especially those involving dry convection, entrainment, and turbulence. To date it has been validated by examining a number of different types of problems, in which it has always performed as well as or better than similar models. These intercomparisons include LES studies of a convective boundary layer (Nieuwstadt et al., 1993) and entrainment in a radiatively cooled smoke cloud (Bretherton et al., 1999).

1.2.2 Findings

We ran and analyzed 2D UU CRM simulations of prior 3D (Glendening and Burk 1992; Glendening 1994) and 2D (Alam and Curry 1995; AC95) lead-generated plume simulations to gauge the impacts of differences in model physics. The UU CRM simulations were run without microphysical and

radiative processes to allow comparisons to be made with the other models. Glendening and Burk's simulations involved a 200-m wide lead with various orientations. The corresponding CRM simulations exhibited generally good agreement with the LES results, especially with respect to sensible heat fluxes and plume penetration depths, although there were some differences in the shapes of the plume and the maximum vertical velocities.

AC95 simulated a plume over a 10-km wide lead in quiescent environment. After six hours of integration, AC95 found that the plume penetrated to an altitude of approximately 2 km, while in the corresponding UU CRM simulation, the plume height was less than 800 m. A possible explanation for the disparities between these results is the more advanced turbulence closure scheme employed in the UU CRM.

Additional evidence that the CRM is accurately predicting plume height may be obtained by comparing model results with those from theoretical methods. A similarity solution for a line source of buoyancy flux in a stratified fluid (Emanuel 1994) may be obtained for the case where the large-scale geostrophic wind is parallel to the lead. The left portion of Figure 1 (see section 1.3) compares CRM results with those obtained from similarity theory. The excellent agreement with theory leads us to believe that we are handling the basic physics of the problem accurately.

Comparisons with theory become more complicated when the geostrophic cross-lead wind is non-negligible. The right side of Figure 1 compares the heights for such a situation calculated from the theoretical dimensional solution given by Glendening and Burk (1992) with CRM results. For this case, the lead was 200 m wide. For comparison, the LES results from Glendening (1994) are included on the plot. The excellent agreement between theory, LES, and CRM results again suggests that these plumes are being simulated adequately. These analytical solutions for the plume height form the basis for a parameterization that more accurately distributes in the vertical the heat and moisture released by leads.

Based on our CRM results for cases with fixed surface temperatures, it appears that the addition of microphysical and radiative processes has the greatest impact upon the more energetic circulations, such as those associated with wider leads. As an example, for a 6400-m wide lead with wind parallel to the lead, the structure of the resulting plume does not change appreciably when microphysical and radiative processes are included, but the height and maximum vertical velocity does increase. For the first simulation, the plume reaches a height of about 630 m. The addition of microphysics increases the

plume height by 60 m (due to latent heat release in the plume), and the addition of radiative processes increases the height by another 90 m (due to radiative heating of air over the lead). Thus, the inclusion of the additional physics increases the plume height by 24 percent.

Allowing the surface temperature of the snow or ice to evolve in response to the surface energy balance has a significant impact on the turbulent and upwelling IR radiative fluxes, and thus on the net surface flux. During SHEBA, a typical January snow surface temperature under clear skies was -38 deg C, and under cloudy skies was -20 deg C. The corresponding observed turbulent and upwelling IR radiative fluxes were about 20 W/m² and 60 W/m² greater under cloudy skies. This demonstrates that prognosing the snow surface temperature is particularly important for modeling the response of the surface heat budget to clouds, including those produced by leads.

By extending this method to the thin ice layers that form on refreezing leads, we are able to estimate the impacts that the refreezing process has upon the surface fluxes. We found that heat fluxes may still be substantially enhanced over a partially refrozen lead, but that the latent heat flux falls off rapidly as a lead refreezes. This rapid decrease in latent heat fluxes, and subsequent decrease in a condensed phase plume, can have a major impact both above and downwind of the lead. Nonetheless, even with an ice layer of up to 0.5 m thick, net heat fluxes at the surface of over 100 W/m² were observed, nearly two orders of magnitude greater than those observed over an unbroken snow/ice surface.

Wintertime air-sea temperature differences of 20 to 40 K over the leads produce large fluxes of heat and moisture into the Arctic atmosphere. Under typical wintertime conditions, our simulated convective plumes penetrated to heights of hundreds of meters and impacted surface fluxes over 50 km downwind. The simulated convective plume rose to a height of nearly 200 m, and was composed primarily of cloud ice. Immediately above the lead, the cloud ice mixing ratio reached a value of approximately 0.1 g/kg. Lower values extended to nearly 50 km downwind. The radiatively active plume markedly increased the downwelling longwave radiation above both the lead and the snow/ice surface.

Curry et al. (1993) proposed that lead-produced condensate plumes can significantly alter the surface IR radiation budget. They concluded that lead-induced low-level ice crystal clouds may make a significant contribution to the wintertime cloud fraction and thereby play an important role in determining the equilibrium sea ice thickness. Pinto and Curry (1995) calculated that

lead-induced cloudiness increases the downwelling IR flux received at the surface by up to 70 W/m^2 . The large-scale effects of the lead on the surface fluxes also depends on the persistence of the lead-produced cloudiness. If the lead quickly closes, the only lead effects remaining would be the radiative effects associated with the condensate plume.

Leads affect the surface heat budget in several ways. The water temperature of a lead that has not yet frozen is about -2 deg C , whereas the temperature of the snow/ice surface is typically about -40 deg C , and that of the surface air over snow/ice is about -30 deg C under mid-winter clear sky conditions. Because turbulent sensible and latent heat fluxes depend on the differences in temperature and moisture between the air and the underlying surface (as well as the wind speed), the turbulent fluxes over the lead will be much larger than those over the ice. If a 3-km wide lead suddenly opened, the sensible heat fluxes (for typical SHEBA mid-winter conditions) would change from -15 W/m^2 (over snow/ice) to about $+500 \text{ W/m}^2$ (over water), and the latent heat fluxes (due to evaporation of water) would change from 0 to about $+110 \text{ W/m}^2$.

The infrared (IR) radiative fluxes are also an important component of the surface heat budget of the Arctic. For typical clear-sky SHEBA mid-winter conditions, the downwelling IR radiative flux at the surface is about 130 W/m^2 . The upwelling IR at the surface depends on the surface temperature. Therefore, it is much greater over the lead than over snow/ice. If a lead suddenly opened, the upwelling IR flux would increase from about 160 W/m^2 to about 300 W/m^2 .

By combining the various components of the surface heat budget, we see that the net upward heat flux would increase from its snow/ice value of about 16 W/m^2 to about 800 W/m^2 if a lead suddenly opened. However, this is not the end of the story, because once a lead opens, the large fluxes over it produce a convective plume that modifies (or feeds back on) the fluxes over the lead and over the snow/ice downwind of the lead.

Over the lead, the most important modification is to the wind speed. The convective plume causes the wind speed over the lead to increase by bringing air from higher levels with greater wind speed down to the surface, and by the inflow into the plume at low levels over the lead. A less important effect is due to cloud formation in the convective plume, which increases the downwelling IR radiative flux. As a result of these feedbacks, the over-lead flux of sensible heat increases from about 500 to 700 W/m^2 , while that of latent heat increases from 110 to 170 W/m^2 , and the downwelling IR

radiative flux increases from 130 to 160 W/m². The net effect is to increase the over-lead heat flux from about 800 to 1000 W/m².

Over the snow/ice downwind of the lead, one might expect that the surface air would be warmed and moistened by the lead. However, except immediately downwind of the lead, this is not the case because the convective plume is elevated. The maximum warming and moistening effects due to the convective plume occur at a height of about 50 m (for a 3-km wide lead). As a consequence, the convective plume primarily affects the snow/ice surface radiatively. The result is a decrease in the net upwelling IR radiation of 12 W/m², from 32 to 20 W/m². This is mainly due to the increased downwelling IR flux, which is due to the elevated, cloudy plume. The plume radiates downward from a level in the atmosphere which is several degrees warmer than at the surface due to temperature inversion. The overall impact of the lead on the surface heat budget over the snow/ice is to decrease the net upward flux by 11 W/m², from 16 to 5 W/m². This means that the surface cools less rapidly than it would if the lead and its plume were not present.

Obviously, the water surface in the lead cools much more rapidly than it did before the lead opened, when it was insulated by 2 m of ice and snow. What is the net effect of the lead on the surface heat budget? It depends on the lead fraction (the fraction of surface area occupied by open water). For a lead fraction of 6.25 percent, the weighted average of the fluxes over the lead and the sea ice is about 65 W/m², compared to about 16 W/m² over the sea ice before the lead opened. The net effect of the lead in this case is to increase the transfer rate of heat from the ocean to the atmosphere by about 50 W/m². This is enough to warm the entire atmosphere by about a half degree C per day, which is significant.

The effects of changing the lead width were also examined using the full two-dimensional model. Halving the width of the lead reduced the strength of the lead-induced circulation, and reduced the effects of the plume downwind. When the lead width was doubled, the opposite effects were seen. The wider lead was responsible for an enhanced circulation strength, and thus enhanced turbulent fluxes above the lead.

To examine the effects of lead refreezing, a simulation was run in which the lead was covered with a 2.5 cm thick layer of ice. Due to the insulation of the ice, the upwelling IR and turbulent fluxes over the lead are reduced. The latent heat flux is reduced to a much larger extent than the others, however. This, subsequently, led to a decrease in the production of the ice cloud plume, and a decrease in the downwelling IR over the entire domain. Owing to the

magnitude of the decreased fluxes over the lead, there is a decrease in the domain-averaged net upwards heat flux, despite the doubling in net heat flux over the snow/ice.

In another simulation, in which the ambient relative humidity is decreased with respect to the basic simulation, the downwelling IR flux again plays a deciding role in the surface heat budget. Due to entrainment with the drier environmental air, the lead-induced plume contains substantially less cloud ice.

The "mosaic" method is commonly used to represent the effects of leads in global climate models. In the mosaic method, the fluxes are calculated separately over the leads and over the sea ice, using the horizontally averaged atmospheric properties. These atmospheric properties are in turn affected by the weighted average of the fluxes. Figure 4.8 (see section 1.3) compares results from the "mosaic" method with the domain-averaged results from the basic "resolved" lead simulation and the initial conditions. Plots of wind speed, air temperature, water vapor mixing ratio, and cloud ice mixing ratio are included.

With the mosaic method, a lead does not form an elevated plume; instead, a shallow fog layer develops, which actually warms the sea ice. The surface air was both warmer and more humid when compared with the standard "resolved" lead case. These factors substantially reduced the turbulent fluxes over both open water and snow/ice. The mosaic method predicts that the fluxes over the lead are about 900 W/m^2 , which is an underestimate of 100 W/m^2 . The mosaic method also estimates that the net effect of the lead is to increase the net upward heat flux by about 35 W/m^2 compared to the no-lead situation, which is 15 W/m^2 , or 30 percent, too low. Based on these results, we concluded that the mosaic method is inadequate to represent the atmospheric effects of leads.

An additional consequence of the differences between the "resolved" and "mosaic" simulations are the differences in the long term evolution of their convective plumes as they advect away from the lead over unbroken snow/ice. Figure 4.9 (see section 1.3) displays the time evolution of cloud-ice profiles for both the "resolved" lead and "mosaic" simulations. The "mosaic" simulation developed a surface-based plume that tended to be reabsorbed by the snow/ice surface relatively quickly when allowed to advect into a lead-free area, whereas the "resolved" lead simulation produces an elevated cloud ice plume similar in appearance to the SHEBA LIDAR imagery for 20 Jan 1998 shown in Figure 4.6 (see section 1.3). The persistence of the "resolved" plume

compared with the "mosaic" plume is likely to have significant consequences for the surface heat budget over a wide area, due to the impacts of a cloud upon the downwelling IR flux.

The significant differences in both the quantitative and qualitative nature of the results indicate that the "mosaic" method is inadequate for parameterizing the atmospheric effects of wide wintertime leads. It is clear that such leads can have a major impact upon the Arctic climate through numerous processes. As presently handled in large-scale models, however, many of these are neglected. Leads do not merely act to enhance the large-scale surface fluxes, but instead form a complex series of feedbacks involving the lead itself, the atmosphere, and the snow/ice surface. Factors such as lead size and orientation are generally absent from present large-scale models, which can impact the height, extent, and eventual fate of any resulting lead-induced plume. Unfortunately, it appears unlikely that lead effects can be adequately parameterized by means of a simple method.

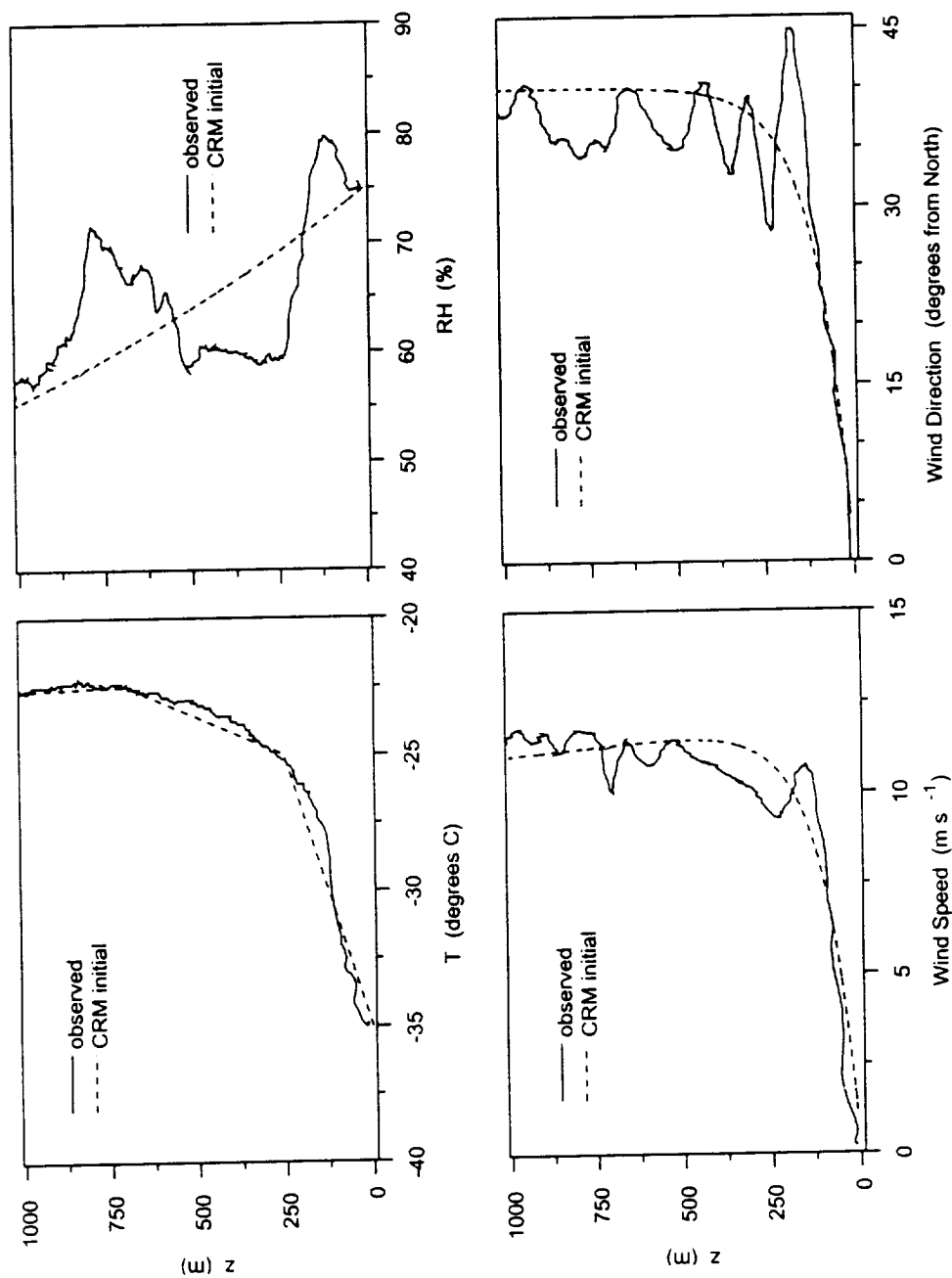


Figure 4.3. Observed atmospheric soundings from SHEBA rawinsondes for January 18, 1998, 23:16 UTC. Dashed lines indicate the simplified profiles used in initializing the CRM.

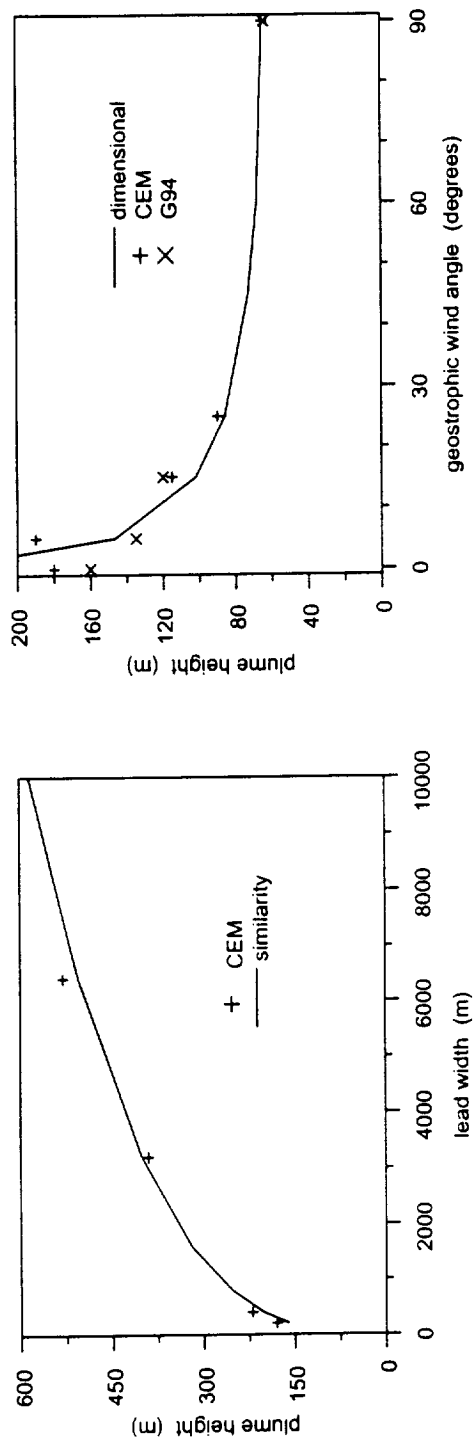


Figure 1: Comparison of simulation-derived and theoretical plume heights for various lead widths when the geostrophic wind is lead-parallel (left), and for various geostrophic wind angles for a 200-m wide lead (right).

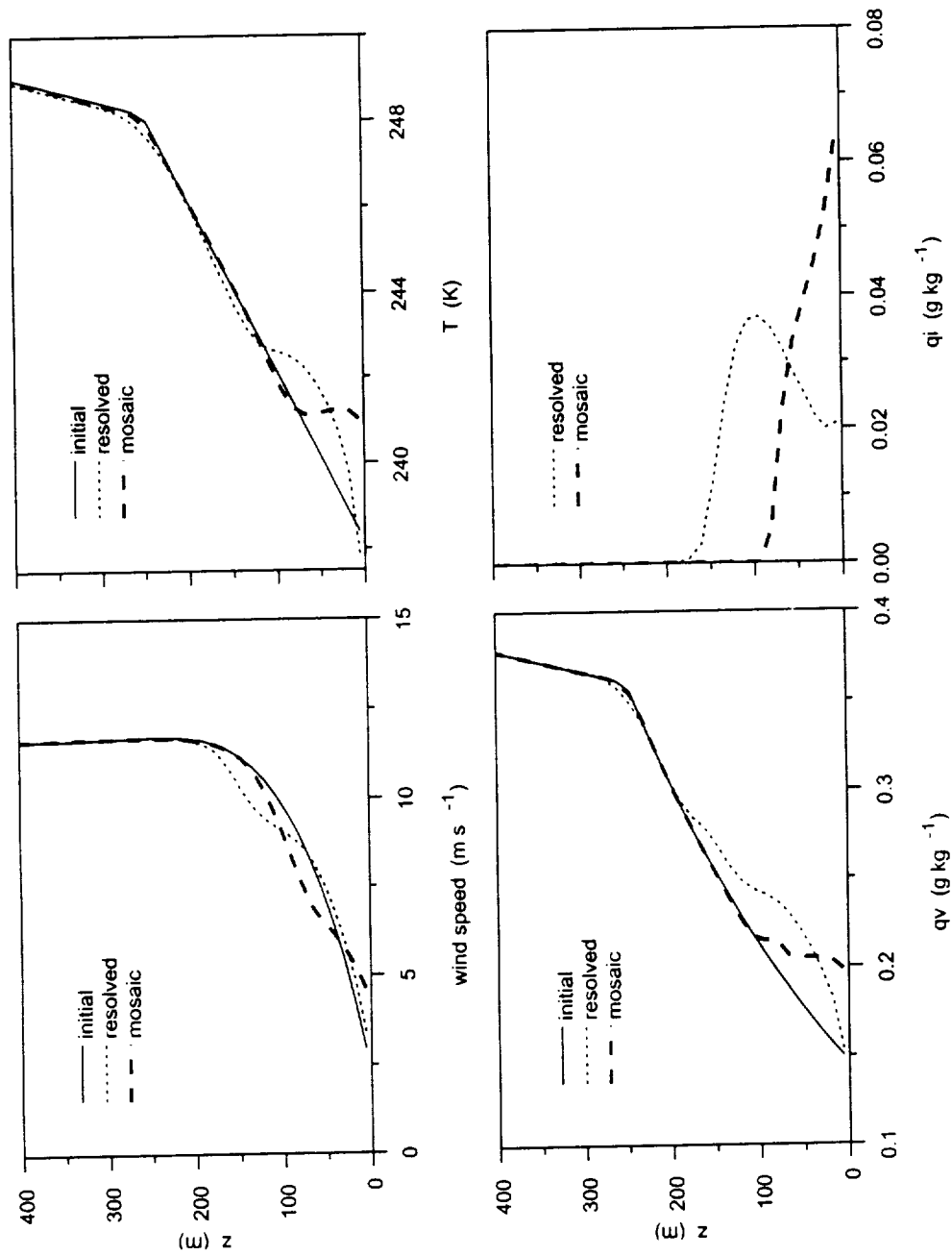


Figure 4.8 Domain-averaged initial conditions and results after 1.5 h of wind speed, air temperature, water vapor mixing ratio, and cloud ice mixing ratio for both the “resolved” and “mosaic” simulations.

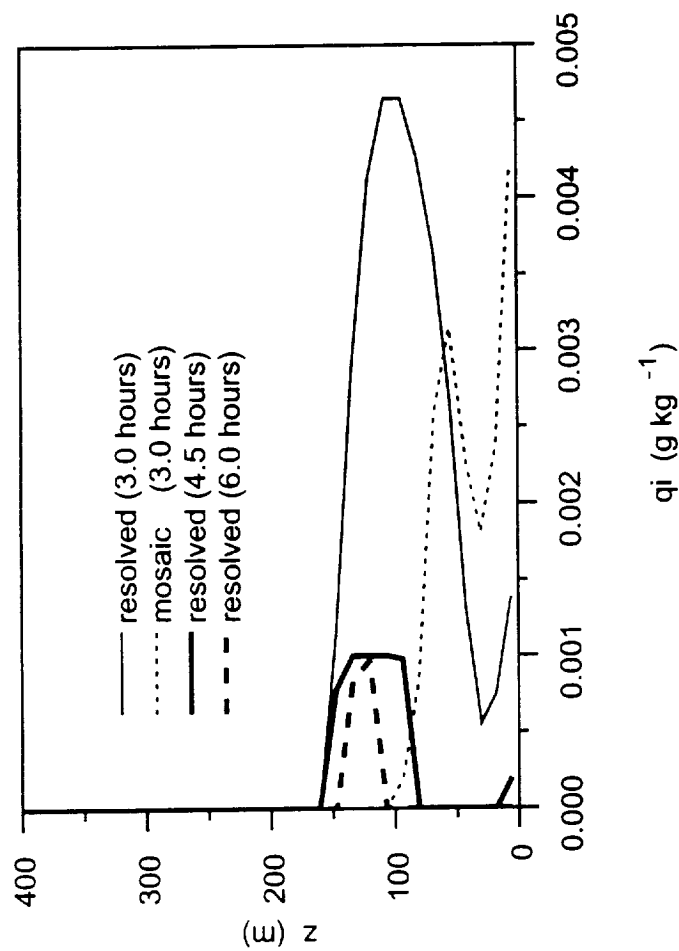


Figure 4.9. Time evolution of cloud-ice profiles for both the “resolved” lead and “mosaic” simulations.

NOAA DABUL LIDAR QUICK LOOK - 1/20/98 (UTC)

photons per bin per shot

0.0e0 9.3e-3 2.7e-2 6.2e-2 1.3e-1 2.6e-1 5.1e-1

Km

1.5

0.0

04:20 06:20 08:20 10:20 12:20 14:20 16:20 18:20

Figure 4.6. LIDAR imagery from the SHEBA site for January 20, 1998.

2 Students and Postdocs Supported

This grant supported Michael Zulauf's participation in the project as a graduate student for one year. The grant also supported Dr. Shuairan Liu's and Dr. Qiuqing Zhao's participation in the project as postdoctoral researchers.

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